Discovery of molecular hydrogen in a high-velocity cloud of the Galactic halo

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The Galactic halo contains in many directions clouds of neutral hydrogen with high radial velocities[1]. These high-velocity clouds mostly have motions towards the Galactic plane but do not follow the rotational movement of the disc. Since distance information for high-velocity clouds is sparse[2,3] and the kinematics cannot be fixed from just the radial velocites, a closed theory about the origin of high-velocity clouds is not available today. One idea is that these clouds are the cooling part of a Galactic fountain[4,5]. Here the gas would predominantly originate in the metal-rich Galactic disc. The other suggests that they represent metal-poor gas falling onto the Milky Way from intergalactic space[6,7]. The presence of molecular hydrogen, whose formation requires that dust and thus metals are present, might discriminate between the two theories. Here we report the discovery of molecular hydrogen in a Galactic high-velocity cloud in the southern sky. For the same cloud we derive an iron abundance which is half of the solar value. Thus, all evidence points to a Galactic origin for this high-velocity cloud.

An earlier search for molecular gas in the Galactic halo was limited to radio observations of the carbon-monoxide molecule (CO)[8,22]. The by far most abundant molecule in the interstellar medium, molecular hydrogen (H_2), can in its cold form only be observed in the far ultraviolet (FUV) domain in absorption against bright background sources. This method requires a telescope working outside of the earth's atmosphere. The echelle spectrograph of the Orbiting and Retrievable Far and Extreme Ultraviolet Spectrometer (ORFEUS)[9] is the first instrument capable to investigate the H_2 molecule in the FUV outside the Milky Way disc. Previous instruments could not match ORFEUS because of their wavelength coverage or the lack of sensitivity.

For the investigation of the H_2 absorption in Galactic high-velocity clouds (HVCs) several lines of sight towards bright stars in the Magellanic Clouds are available from ORFEUS. The two Magellanic Clouds are the most nearby satellite galaxies of the Milky Way. The HVC in front of the 50 kpc distant Large Magellanic Cloud (LMC) at $v_{\mathrm{rad}} = +120\,\mathrm{km\,s^{-1}}$ is seen in almost all absorption spectra of LMC stars[10,11]. That HVC thus was known to have a substantial extent in the sky[12] and therefore most likely is a foreground cloud of the Milky Way halo.

From the four ORFEUS spectra of LMC stars the one to the B type star HD 269546 ($l = 279.32$, $b = -32.77$) shows the presence of H_2 at $+120\,\mathrm{km\,s^{-1}}$. This line of sight is the one in our sample with the highest column density of atomic hydrogen[13]. For all other LMC spectra no clear absorption is seen at HVC velocites, probably a result from a combination of lower H I column densities, lower signal-to-noise ratios and line blending. Nine H_2 absorption lines from the lowest 7 rotational states and free from line blends were found in the spectrum of HD 269546 and for 5 additional transitions upper limits for the equivalent

widths were determined (Table 1). Fig. 1 shows part of the spectrum where some of the detected H_2 absorption features are found. Fig. 2 shows the Werner Q(2),0-0 line at 1010.941 Å, plotted in velocity scale as an example for the H_2 absorption pattern. The H_2 absorption at $v_{\rm rad} = +120\,{\rm km\,s^{-1}}$ matches perfectly the neutral hydrogen emission profile of this sight line[13] and there is no doubt that both neutral and molecular hydrogen belong to this HVC.

For the quantitative analysis we made use of a standard curve-of-growth technique. We measured equivalent widths for the H_2 absorption at +120 $\rm km\,s^{-1}$ and constructed curves of growth for each roational state J individually which collectively fit the velocity-dispersion parameter $b = 9$ $\rm km\,s^{-1}$. The high b-value indicates that the gas is turbulent. We find the H_2 column densities $N(J)$ to be as: $\log N(0) \leq 14.2$, $\log N(1) = 14.6 \pm 0.2$, $\log N(2) = 14.8 \pm 0.2$, $\log N(3) = 14.8 \pm 0.2$, $\log N(4) = 14.7 \pm 0.4$, $\log N(5) \leq 14.7$, $\log N(6) \leq 14.9$.

The total H_2 column density in this HVC is small, $N(H_2) = 2.2 - 3.6 \times 10^{15}$ $\rm cm^{-2}$. Comparison with the column density of neutral hydrogen $N(\text{H\,I}) = 1.2 \times 10^{19}$ $\rm cm^{-2}$, derived from the older Parkes 21-cm emission profile[13], shows that the proportion of H_2 to H I is similar to that found in diffuse gas in the Galactic disc[14]. It is indicative of well illuminated gas with low dust content.

The distribution of column densities over the rotational states can be used to roughly estimate the excitation conditions in the H_2 gas[15]. The temperature of the H_2 gas is $\geq$ 1000 K, derived by a fit of the population of the rotational levels to a theoretical Boltzmann distribution. This value most likely is not the actual kinetic temperature, but represents the excitation through UV photons from the Galactic disc. In sharp contrast, the relative abundance of para-H_2 (even J numbers) and ortho-H_2 (odd J numbers) for $J \leq 3$ is ≈ 1. Thus the ortho-to-para ratio must have been thermalized by proton exchange[16] with H^+ to

a gas temperature below 100 K. The discrepancy between these two temperature ranges is a sign that the gas is *not* in thermodynamical equilibrium. Further support for this is given by the fact that the observed low H_2 column density can hardly be described with approved theoretical models of H_2 formation- and destruction processes[17] in regard to the strength of the radiation field from the Milky Way disc.

Recent H I data from Parkes[18] (Fig. 3) show that our sight-line crosses the HVC at $+120\,\mathrm{km\,s^{-1}}$ in a region between two denser cores in a much larger complex. It shows spatial similarities to Chain A, recently found to be at a distance between 2.5 and 7 kpc[3]. In view of the structure of the HVC it seems plausible that the cloud core recently has fallen apart. In that case, cold H_2 from the cloud core was exposed to the unshielded UV flux from the Galactic disc that currently photodissociates the H_2 gas.

In order to further explore the origin of the HVC in front of the Magellanic Clouds we have combined ORFEUS data with public data from the International Ultraviolet Explorer (IUE) and have determined the iron abundance in the HVC component at $+120\ \mathrm{km\,s^{-1}}$. From an analysis of five Fe II absorption lines we derive $b = 9\ \mathrm{km\,s^{-1}}$ and a column density of $\log N(\mathrm{Fe\,II}) = 14.3 \pm 0.2$, in good agreement with an earlier investigation[19]. The b-value is the same as for H_2, supporting it is the same gas. The iron abundance is $\log\,[\mathrm{Fe\,II/H}] = -4.8$, which is half of the solar value[20]. This ratio is based on $N(\mathrm{H\,I})$ from the older $15'$ beam Parkes measurement. In view of this high metallicity we can rule out that the gas, and thus the H_2, is of primordial origin or from intergalactic space[23].

Our results favour the Galactic fountain model[4,5] as explanation for the origin of the HVC gas in front of the LMC. In this model hot gas is ejected out of the Galactic disc, cools down and falls back onto the Galactic plane. The molecular hydrogen then must have been formed

within the cooled halo cloud and at least a small amount of dust must be present in that HVC.

Theoretical considerations[8] show that molecular hydrogen can form in HVCs once the hydrogen volume density $n(\mathrm{H\,I})$ exceeds a critival value. This critical volume density depends on the H I column density, the amount of dust, the radiation field, the gas temperature and the velocity dispersion parameter b. We have found $b = 9\,\mathrm{km\,s^{-1}}$ for our HVC gas, indicating that H_2 might form at volume densities as low as $n(\mathrm{H\,I}) \approx 10\,\mathrm{cm^{-3}}$. The *actual* volume density can only be determined assuming a certain distance to the HVC in combination with assumptions for the depth-structure. However, the uncertainties for these parameters are too high to judge whether the theoretical models can derscribe the observations we have presented here.

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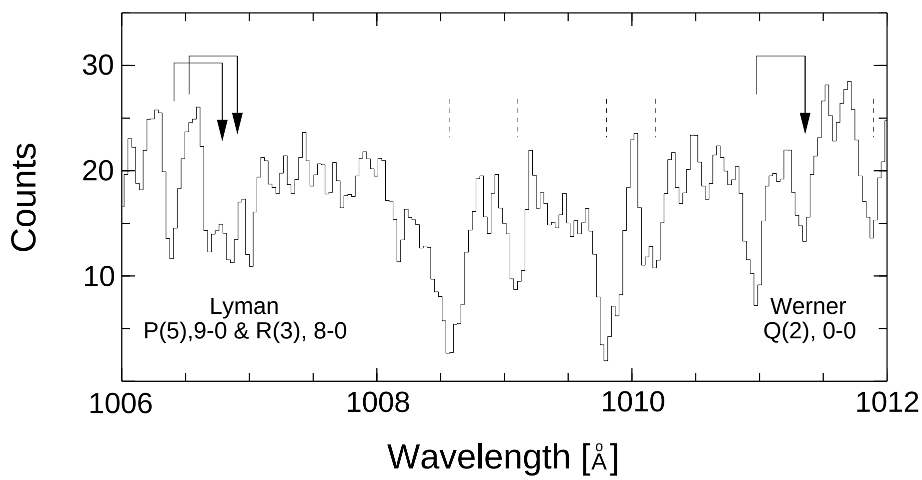
Table 1: H_2 equivalent widths for the HVC gas towards HD 269546

Line	λ [Å]	$\log f\lambda^{21}$	W [mÅ]
L R(0),4-0	1049.366	1.39	≤ 30
L R(1),8-0	1002.457	1.26	34 ± 19
W Q(1),1-0	986.798	1.56	75 ± 22
W Q(2),0-0	1010.941	1.38	65 ± 22
L R(2),4-0	1051.497	1.19	54 ± 23
L P(2),7-0	1016.472	1.01	≤ 57
L P(2),11-0	975.343	0.81	≤ 42
L P(3),3-0	1070.142	0.89	33 ± 17
L R(3),4-0	1053.976	1.18	47 ± 23
L R(3),8-0	1006.418	1.19	63 ± 30
L R(4),4-0	1057.379	1.17	46 ± 23
L P(5),4-0	1065.594	1.00	≤ 31
L P(6),3-0	1085.382	0.94	≤ 54
L R(6),7-0	1030.064	1.17	65 ± 25

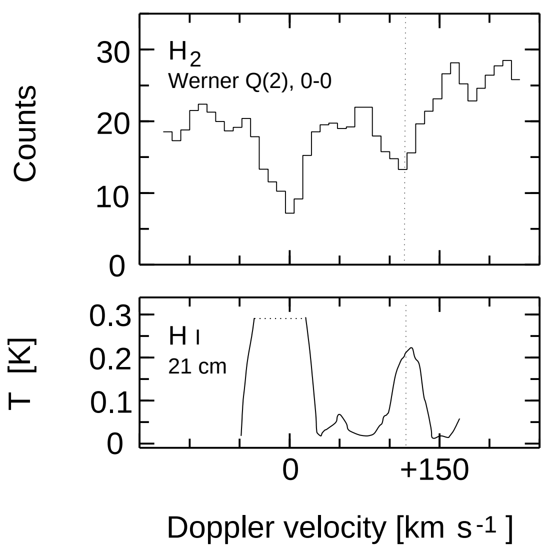
Fig. 1: The spectral region between 1006 and 1012 Å in the ORFEUS spectrum of HD 269546. The solid markings indicate H_2 absorption lines with the Galactic component at 0 $\mathrm{km\,s^{-1}}$ and the arrows the HVC component at a Doppler velocity of $\sim +120$ $\mathrm{km\,s^{-1}}$. Other identified absorption lines, which are of no importance here, are marked with dashed lines.

Fig. 2: Comparison between the H_2 absorption profile (upper panel) and the H I emission profile (lower panel) for the HVC gas in direction of HD 269546. The H_2 Q(2),0-0 line at 1010.941 Å in the Werner band (here plotted in the Doppler velocity scale, LSR) reveals H_2 absorption from HVC gas near $+120$ $\mathrm{km\,s^{-1}}$ (upper panel). At this velocity, emission from neutral hydrogen[13] (lower panel) is present, too.

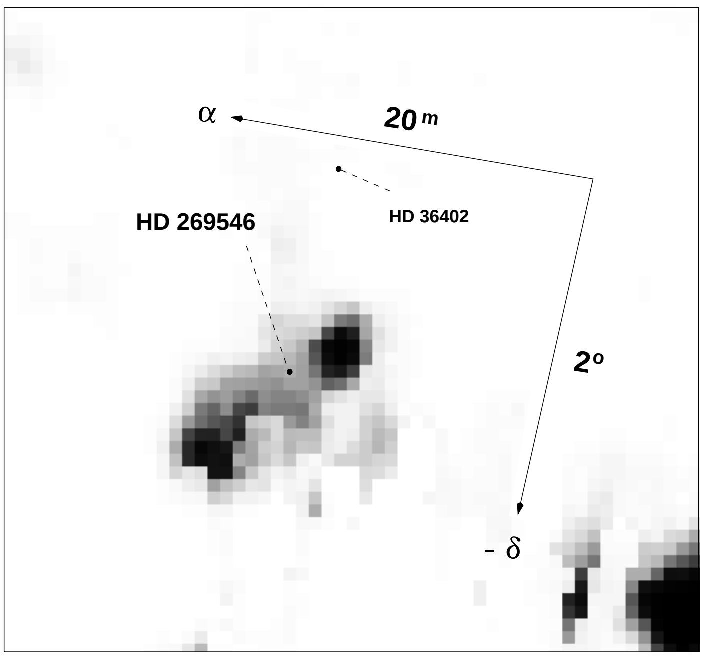
Fig. 3: Map of the peak intensities (J2000) for neutral hydrogen emission from the HIPASS survey (preliminary, uncalibrated) for velocities $v_{\mathrm{LSR}} = 105$ - 145 $\mathrm{km\,s^{-1}}$ in the field centred on HD 269546. The map displays only the high intensities (dark structures). The line of sight towards HD 269546 passes between two denser H I clumps in the high-velocity cloud. The line of sight to the LMC star HD 36402, on which absorption and emission is known at the same velocity[10], is also indicated. The map was made available by the HIPASS team[18].



Counts
30
20
10
Lyman
P(5),9-0 & R(3), 8-0
Werner
Q(2), 0-0
1006
1008
1010
1012
Wavelength [Å]



Counts
30
20
10
0
H_2
Werner Q(2), 0-0
T [K]
0.3
0.2
0.1
0
H I
21 cm
0
+150
Doppler velocity [km s^{-1}]


α
20 m
HD 36402
HD 269546
2o
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